

## Comparison of microbial quality of irrigation water delivered in aluminum and PVC pipes



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### ABSTRACT

Microbial quality of irrigation water attracts substantial attention due to the increased incidence of gastrointestinal illness caused by contaminated produce. Little is known about the changes in microbial quality of water during its delivery to crops. Studies were conducted to compare the biofilm formation and changes in microbial water quality in aluminum and PVC irrigation pipes. Irrigation events were conducted weekly and sections of irrigation pipe (coupons) analyzed for total protein, for total and fecal coliform bacteria, and for *Escherichia coli*. Coliform and *E. coli* concentrations along with nitrate, orthophosphate, and total organic carbon were monitored in the intake surface water, output irrigation water, and measured in residual standing water in pipes just prior to each irrigation event. Proteins accumulated to a greater extent in aluminum-associated biofilms than in plastic-associated biofilms. Numbers of total coliforms associated with aluminum coupons increased with time while numbers of total coliforms associated with plastic coupons fluctuated. Nitrates disappeared in standing water after one week in aluminum pipes and remained present in plastic. No detectable *E. coli* remained in standing water in both types of pipe. There was a high probability that coliform concentrations in output irrigation water were different from the intake concentrations in plastic pipes but not in aluminum pipes. Further research is required to evaluate how pipe material may affect the potential of biofilms in irrigation distribution systems to serve as reservoirs of pathogens that can be disseminated to crops during irrigation.

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### 1. Introduction

Microbial quality of irrigation water is attracting substantial attention due to the increased incidence of gastrointestinal illness caused by contaminated produce. Produce accounted for nearly half of all food-borne illnesses in the USA in 1998–2008 (Painter et al., 2013). Contaminated irrigation water has been directly implicated in several of these outbreaks. Previous research has shown that pathogenic microorganisms from irrigation water can survive within leaf and other plant tissues (Brandl, 2006). Presence of pathogens is of primary concern for the wastewater irrigation in developing countries (Qadir et al., 2010), and has long been defined as a source of risk in the reuse of the effluent water (Toze, 2006). Rural surface waters in humid regions present another

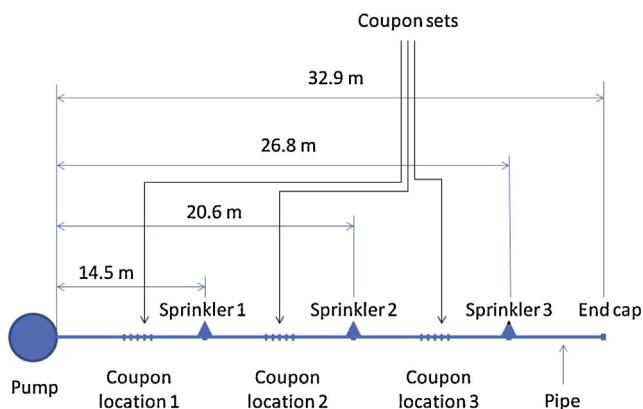
source of irrigation water that is often impaired due to microbial contamination (Jamieson et al., 2004). Considering the increasing scarcity of water resources, there is little doubt that more information is needed regarding the fate and transport of pathogens in irrigation waters (Gerba, 2009; Pachepsky et al., 2011).

Water delivery systems are known to change microbial water quality. It has been shown that practically any microbe (including pathogens) present in water may attach to, or become enmeshed, in biofilms. Biofilms are a complex mixture of microbes, organic, and inorganic material accumulated within a microbially-produced polymeric matrix, which is attached to the inner surface of the distribution system. Interactions with biofilms in complex water systems (Berry et al., 2006; Juhna et al., 2007; Wingender and Flemming, 2011) has been shown to impact pathogen persistence and survival. Biofilms are known to form in irrigation water distribution systems; they have been extensively studied to better understand the nature of irrigation system clogging and biofouling (Dehghanian et al., 2004; Yan et al., 2009; Li et al., 2012).

The effect of biofilms in irrigation pipelines on microbial quality of irrigation water was first suggested by Sadovski et al. (1978).

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**Fig. 1.** Layout of experimental irrigations systems.

They monitored the effluent from drip irrigation lines for traceable micro-organisms added to treated wastewater and observed small peaks in bacterial colony counts on days 2 and 8 and in viral counts on day 8. They hypothesized that the elution of micro-organisms from the irrigation system was affected by adsorption of viruses and bacteria to the organic matter which lined the inside walls of the irrigation system; repeated irrigations may have resulted in the release of the organisms. Pachepsky et al. (2012) and Shelton et al. (2012) reported high probabilities of the change in total coliform, fecal coliform, and *Escherichia coli* concentrations in water after it passed through an irrigation system. The presence of coliforms in biofilms on the internal surfaces of pipes was documented in those works.

Materials of irrigation system pipes and tubing vary greatly. Pipe material has been shown to affect biofilm formation in drinking waters (Hallam et al., 2001; Lehtola et al., 2004; Morvay et al., 2011) and to influence both biofilm biomass accumulation (Niquette et al., 2000) and microbial diversity in biofilms (Yu et al., 2010).

All of the factors controlling formation and microbial survival in biofilms found in drinking water distribution systems are represented in irrigation water delivery systems. However, these two types of pipe-based water delivery systems have quite different parameters, including temperature and pH, nutrient contents and proportions, microbial communities, pipe and sediment material, hydraulic regimes, and disinfection techniques.

The objective of this work was to test the hypothesis that the pipe material used in irrigation systems can significantly affect native *E. coli* concentrations in water passing through the irrigation system and discharged onto crops. Coliforms and *E. coli* were selected as the common indicator microorganism used to characterize microbial quality of irrigation waters (Steele and Odumeru, 2004).

## 2. Materials and methods

### 2.1. Field setup and sampling

Two irrigation systems, one made of used gray aluminum pipes and another one of new white PVC pipe, were assembled at the BARC South Farm Research Site (Beltsville, MD, USA) as shown in Fig. 1. Six-inch (15.24 cm) long segments (coupons) were cut from sections of both sets of pipes. A total of four coupon sets were inserted into each pipeline and were maintained in place using rubber hose and stainless steel clamps placed over the pipe and coupon contact area. Coupons in each set were connected to each other and to the main pipe with Rainway CL300 clamp-on quick latch couplers (Travis Pattern & Foundry Inc., Spokane, WA). The

irrigation system was placed on fairly level ground with a moderate grass cover (estimated slope of 0–2%).

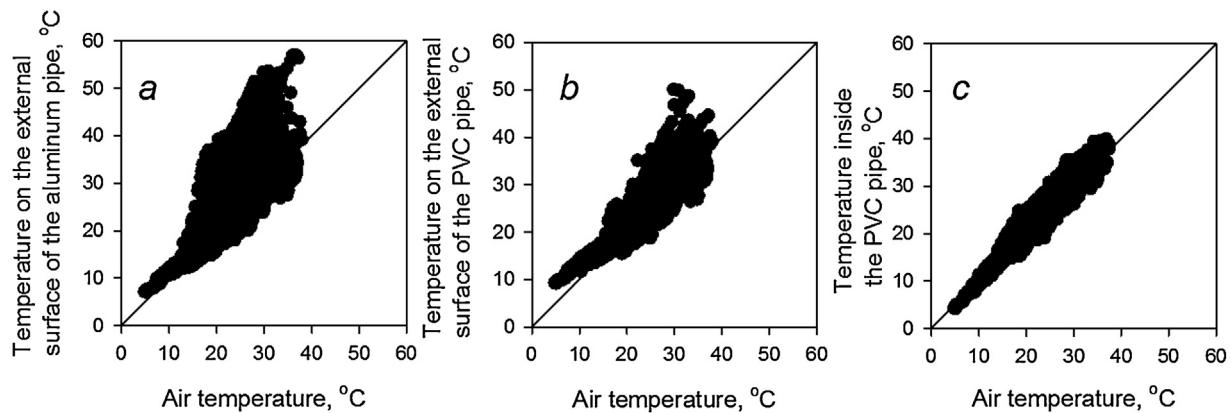
Water from the nearby perennial Paint Branch Creek was used for all irrigation events. Temperature inside the plastic pipe was monitored by a HOBO U20 stage logger (Onset Computer Corporation, Bourne, MA) housed within the pipe with protection from the water hammer effect at the beginning of each run of the irrigation experiment. Temperature at the external surfaces was measured with the HOBO S-TMB-006 probes insulated from ambient conditions by a half inch neoprene sheath.

The first irrigation event occurred on 7/10/12. Subsequent irrigation events were on 7/17/12 (day 7), 7/24/12 (day 14), 7/31 (day 21), and 8/07/12 (day 28); coupons and standing water were analyzed for these four events. Clamps around one of coupons were loosened at each of locations 1, 2, and 3 (Fig. 1) before irrigations, a portion of residual water was collected to WhirlPak (Fort Atkinson, WI) bags, one of coupons was extracted, pipes were moved to close the space left from coupon, and the clamp were tightened to reseal the pipeline. Samples of creek water in triplicate and samples of water from each of the three sprinklers were taken when irrigation was started (hour zero), 1 h later, and 2 h later. All samples were stored and transported to the laboratory on ice. Weekly irrigations continued after day 28, but no samples were taken between 8/07/11 and 9/19/11. On 9/19/11 (day 71) and 9/27/11 (day 79), samples of intake and sprinkler water were taken. On sampling days, the first irrigation was conducted from 8 AM through 10 AM and the second from 10:15 AM through 12:15 PM. The first and the second irrigation events were conducted with aluminum and plastic pipe on alternating weeks.

### 2.2. Microbiological analyses

Water samples were analyzed for total coliform, fecal coliform, and *E. coli* concentrations. Total coliforms and *E. coli* were enumerated using the colorimetric Colilert-18/Quanti-Tray system (IDEXX Laboratories, Westbrook, ME), with appropriate dilutions as described at <http://www.epa.gov/region8/qa/ColiformSOP.pdf>. Results were expressed in most probable numbers per mL (MPN mL<sup>-1</sup>). Thermotolerant coliforms were enumerated on MacConkey agar (Fisher Scientific, Rockville, MD) spread plates incubated at 44.5 °C for 24 h and expressed as colony-forming units per mL (CFU mL<sup>-1</sup>).

Surface-associated cells and potential biofilms were analyzed for *E. coli*, total coliforms, and fecal coliform counts in the same manner as the water samples. Surface-associated bacteria were obtained by scraping the bottom sector of the coupon's inner surface, which constituted 18 in<sup>2</sup> (116 cm<sup>2</sup>). The 3 in (7.62 cm) diameter to be scraped was marked with an indelible marker along the coupon exterior. Prior to scraping, the entire coupon was gently submerged into sterile deionized water and rinsed 3× to remove unattached or loosely attached bacteria and debris. The BD FalconTM cell scraper (Fisher Scientific Catalog #08-771-1C) was used for scraping coupon interiors. In between scrapings, the cell scraper was washed under running water with a bristle brush, disinfected with 70% ethanol, and rinsed with sterile deionized water. The coupon was held vertically over the bottom of a sterile plastic Petri dish. The marked 18 in<sup>2</sup> section was wetted with a 5 mL aliquot of 0.01 M phosphate-buffered saline containing 0.04% Tween 80 (PBS/Tween 80; v/v; Fisher Scientific Catalog #PI28328). The wetted section was repeatedly scraped, wetted, and rinsed for 9 min using a total of 30 mL PBS/Tween 80. All of the rinses were combined and transferred to a sterile 50-mL polypropylene centrifuge tube. If needed, the suspended biofilm was topped off to 30 mL with PBS/Tween 80. The tube was vortexed 3 times for 10 s bursts and then sonicated on ice for 1 min to break apart solid particles.



**Fig. 2.** Observed temperatures in and outside pipes as compared with air temperature.

The suspension samples were immediately analyzed for coliform bacteria as described above for water samples.

Biofilm proteins were determined by the Micro BCA protein method (Thermo Scientific, Rockford, IL) and expressed as  $\mu\text{g protein cm}^{-2}$ .

### 2.3. Chemical analyses

Intake stream and standing water samples were analyzed for nitrate-nitrogen (ion chromatography, Waters Corporation Alliance system, Milford, MA), orthophosphate-P (Lachat Method, Total Phosphorus in Persulfate Digest, 1992, Lachat Instruments, Hach Co., Loveland, CO) and Total Organic Carbon (UV/Persulfate oxidation method, Phoenix 8000, Tekmar-Dohrmann, Cincinnati, OH). Water samples were stored frozen and were thawed and clarified by centrifugation at 9400 rcf, for 10 min at  $4^\circ\text{C}$  prior to analysis.

### 2.4. Statistical analyses

The statistical software PAST (Hammer et al., 2001) was used to apply the Student test to estimate probabilities of average concentrations from replicated measurements being the same, and to apply the Kolmogorov-Smirnov test to estimate probabilities of statistical distributions being the same.

## 3. Results

### 3.1. Temperature

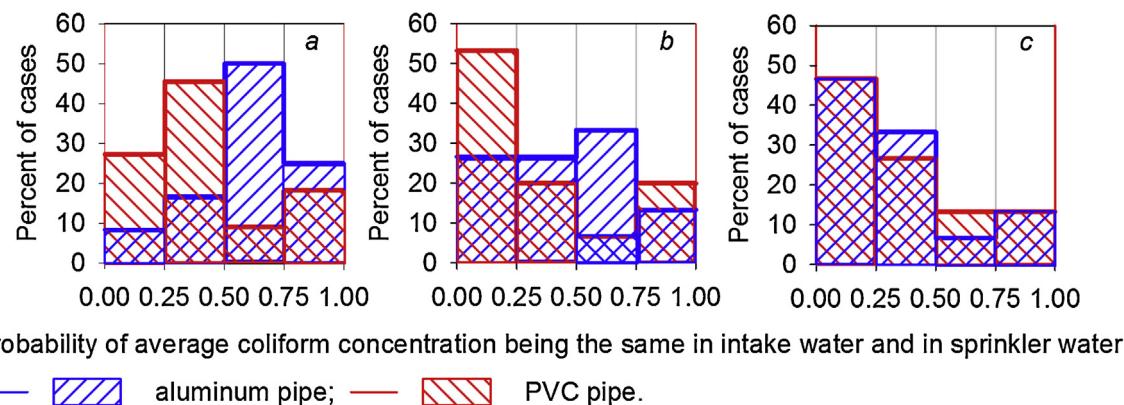
Daily minimum and maximum air temperatures ranged from 18.2 to  $24.5^\circ\text{C}$  and from 20.4 to  $37.9^\circ\text{C}$ , respectively, during first

four weeks of the experiment. Average weekly air temperatures were  $26.5$ ,  $25.7$ ,  $26.1$ , and  $27.5^\circ\text{C}$  for weeks 1, 2, 3 and 4 of the experiment. Temperatures of the external pipe surfaces were substantially higher than air temperatures during day time and slightly higher at night (Fig. 2). These differences were more pronounced for the aluminum pipe (Fig. 2a) than for the plastic pipe (Fig. 2b). The temperature within pipes was generally close to the air temperature (Fig. 2c).

### 3.2. Changes in coliform concentrations in water

For each sampling event and each pipe, the probability was computed that average concentrations of total coliforms were the same in the intake surface water and in the output irrigation water. A histogram was developed showing percentages of sampling events with probabilities being low (0–0.25), medium-low (0.25–0.50), medium-high (0.50–0.75), and high (0.75–1.00); a low probability indicates that the input and output concentrations changed during passage through the system, while a high probability indicates that concentrations were essentially the same. These histograms are shown in Fig. 3.

Visual inspection of Fig. 3a shows that most of those probabilities for total coliforms in aluminum pipes were high and larger than 0.5, whereas most of those probabilities were smaller than 0.5 in plastic pipes. In other words, we observed a better chance for total coliform concentration to be altered in plastic pipes than in aluminum pipes. The probability that the two distribution patterns were the same was also determined; the probability that the two distributions shown in Fig. 3a are similar is only 0.03 (significantly different).



**Fig. 3.** Chances for coliform concentration to remain the same after water passage through the irrigation system: (a) total coliforms, (b) fecal coliforms, (c) *E. coli*.

**Table 1**

Coliform concentrations in water in pipes.

Date	Aluminum		Plastic	
	Intake week before	Water standing above coupons	Intake week before	Water standing above coupons
Total coliforms (MPN mL <sup>-1</sup> )				
7/17	122.6	148.1	117.1	>1161 <sup>a</sup>
7/24	133.8	1321.0	146.0	60.4
7/31	162.6	>102.6 <sup>a</sup>	79.1	37.4
8/07	>2420	41.0	>2420	>146.8 <sup>a</sup>
Fecal coliforms (CFU mL <sup>-1</sup> )				
7/17	11.3	14.0	6.0	0.0
7/24	8.7	20.0	13.3	0.0
7/31	14.7	1895.0	8.7	5.0
8/07	10.0	15.0	4.0	2.0
<i>E. coli</i> (MPN mL <sup>-1</sup> )				
7/17	2.5	<0.3 <sup>b</sup>	2.4	<4.7 <sup>b</sup>
7/24	2.5	<0.3 <sup>b</sup>	3.3	BDL
7/31	5.8	0.0	2.8	0.0
8/07	6.4	<0.1 <sup>b</sup>	6.6	<2.1 <sup>b</sup>

ADL, two or three of three measurements above detection limit; BDL, two or three of three measurements below detection limit.

<sup>a</sup> One of the three measurements was above detection limit; the table entry is computed with measurements within the detection range.<sup>b</sup> One of three measurements was below the detection limit; the table entry is computed with measurements within the detection range.

The average concentration of fecal coliforms also had a better chance to be changed in plastic pipes than in aluminum pipes (Fig. 3b). Probabilities of the average fecal coliform concentrations to be the same at intake and in output sprinkler water were mostly less than 50% in plastic pipes (Fig. 3b), whereas these probabilities were almost uniformly distributed between zero and one in aluminum pipes. The effect of pipe material on the fecal coliform concentration modification was substantial and the probability for two distribution shown in Fig. 3b to be the same was only 0.25.

Finally, very little difference was found in effects of pipe material on *E. coli* concentration change in water passing pipes from intake to sprinklers (Fig. 3c). The probability for the two distributions shown in Fig. 3c to be the same had a high value of 0.89.

### 3.3. Changes in bacteria concentrations in residual water in pipes

Water was left in pipes for a week after each irrigation event. Before the next irrigation event, coupons were removed and water was collected from the pipes where coupons were removed. Coliform concentrations in residual (standing) water that stayed in pipes for a week were compared to concentration in sprinkler water

at the time when the irrigation was stopped (Table 1). Total coliform concentrations significantly changed for some dates ( $P < 0.05$ ) in both types of pipe. Fecal coliform concentrations were variable in aluminum pipes, while consistently decreasing in plastic pipes. *E. coli* concentrations generally decreased to below the detection limit in most of replicated samples of residual water.

### 3.4. Changes in nutrient concentrations in standing water in pipes

Concentrations of three essential nutrients in forms of nitrates, orthophosphate, and dissolved organic carbon were measured in standing residual and in the irrigation water (Table 2). Differences in nitrate concentrations in standing water between aluminum and plastic pipe were dramatic. Nitrate concentrations in the aluminum pipe were depleted to below detection levels during the week in three of four sampling events. On the other hand, nitrate concentrations only slightly decreased during the week in standing water in the plastic pipe. This decrease was statistically significant;  $P(\text{same})$  was always  $<0.01$ .

Much higher  $P$  concentrations were found in residual water as compared with the intake water in the aluminum pipe. On the

**Table 2**

Selected nutrient concentrations, ppm.

Date	Aluminum		Plastic	
	Intake week before	Water standing above coupons	Intake week before	Water standing above coupons
N-NO <sub>3</sub>				
7/17	1.2	0.2	1.2	0.9
7/24	1.0	0.0	1.0	0.9
7/31	1.1	0.0	1.1	0.9
8/07	0.8	0.0	0.8	0.7
P-orthophosphate				
7/17	0.003	0.169	0.003	0.004
7/24	0.003	0.158	0.003	0.005
7/31	0.004	0.097	0.005	0.004
8/07	0.002	0.093	0.001	0.004
Total organic carbon (TOC)				
7/17	3.8	5.1	4.0	3.2
7/24	3.7	4.3	2.0	2.3
7/31	2.6	2.8	3.5	4.0
8/07	3.3	4.7	3.8	4.5

**Table 3**Total coliforms and *E. coli* in biofilms on internal pipe surface (MPN cm<sup>-2</sup>).

Date	Total coliforms		<i>E. coli</i>	
	Aluminum	Plastic	Aluminum	Plastic
7/17	5.53	20.93	0.38	0.04
7/24	6.26	7.76	0.00	0.00
7/31	28.10	17.81	0.00	0.01
8/07	>56.55 <sup>a</sup>	7.58	0.00	0.02

MPN, maximum probable number.

<sup>a</sup> One of three measurements was above the detection limit; the table entry is computed with measurements within the detection range.

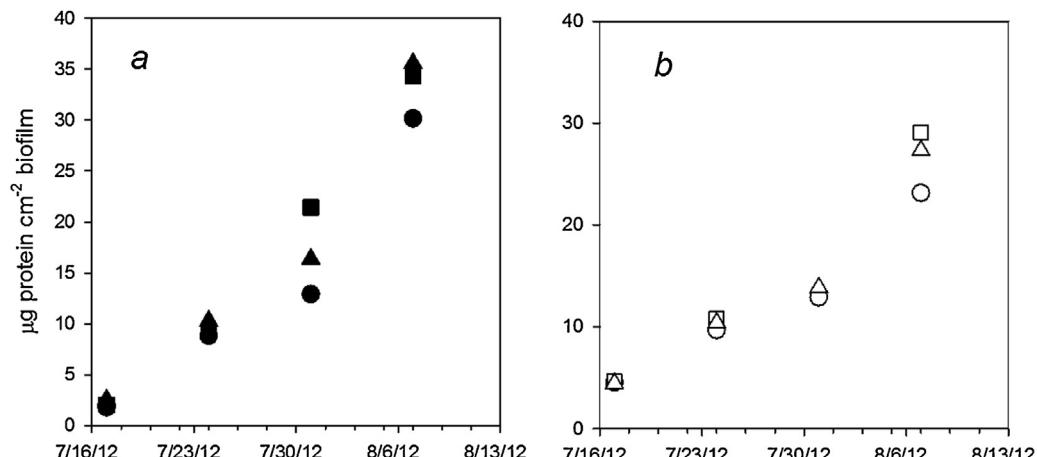
contrary, concentrations of *P* in residual water and in irrigation water were comparable in the plastic pipe, although the differences were significant with *P* (same) <0.1; the average concentration in residual water consistently exhibited a larger *r* than in the intake water. The probability of phosphorus average concentrations being the same in irrigation and in standing water decreased as the experiment progressed.

Differences between average TOC concentrations in intake water and in residual standing water shown in Table 2 were not statistically significant at 0.05 confidence level on 7/17, 7/24, and 8/7 sampling dates. In sampling on 7/31, TOC concentrations appeared to be significantly larger after the week of water storage in both aluminum and plastic.

### 3.5. Biofilm growth and coliforms in biofilms

Data on protein content of the material scraped from inner pipe surfaces indicates substantial and steady growth of biofilm (Fig. 4). Growth was more pronounced in the aluminum pipe as compared with the plastic pipe; overall growth rates were 1.50 and 1.03 µg protein per day in the aluminum and in the plastic pipe, respectively. Visual inspection of graphs in Fig. 4 shows that the growth was not uniform in time and in space. Growth between sampling dates 7/24 to 7/31 was slower than between sampling dates 7/17 to 7/24 and 7/31 to 8/7. Biofilm mass near the sprinkler at location 1 (the closest to the water source) was always smaller than at locations 2 and 3.

Data on concentrations of total coliforms and *E. coli* in biofilms on internal pipe surfaces are shown in Table 3. Total coliforms were uniformly detected while *E. coli* were typically below the detection limit. Whereas total coliforms in biofilms in aluminum pipe increased with time, no increase trend was found for plastic pipes.



**Fig. 4.** Biofilm growth during experiment: (a) aluminum pipe; (b) plastic pipe; ○, ● – coupons at the location 1, ■, □ – coupons at the location 2, △, ▲ – coupons at the location 3; locations are shown in Fig. 1.

## 4. Discussion

These data demonstrate the propensity of biofilms to form in both aluminum and plastic irrigation pipe. However, there were qualitative and quantitative differences between aluminum vs. plastic. Protein accumulated to a greater extent in aluminum associated biofilms than in plastic associated biofilms. Also, the aluminum pipe was generally more conducive to survival and growth of total coliform populations as compared with the plastic pipe. There was a consistent increase in the numbers of total coliforms associated with aluminum coupons, while numbers of total coliforms associated with plastic coupons fluctuated from week to week.

It is possible that new plastic pipes could release some material that specifically inhibits the growth of coliforms. Plastic materials generally contain many additive chemicals such as antioxidants, light stabilizers, lubricants, pigments and plasticizers added to improve the physical and chemical properties of the material. The possibility that toxic organic compounds from the pipes may leach into the drinking water, resulting in toxicity, must be considered (Brocca and Arvin, 2002). The differences in development of biofilms on aluminum pipes as compared with the plastic pipes were similar to the substantial differences in biofilm formation on steel pipe and on polybutylene and polyethylene pipe materials in model systems with drinking water observed by Yu et al. (2010), and on cast iron as compared with plastic materials (Kerr et al., 1999). The biofilm growth rates on plastic materials were 80% of that on cast iron in the work of Kerr et al. (1999) and about 70% in this study. On the other hand, the rugged surface of the old aluminum pipe could be a more hospitable environment for coliform growth in biofilms. Lehtola et al. (2004) observed that the time of use may affect biofilm development in pipelines. In their work, the formation of biofilm was slower in copper pipes than in the PE pipes, but after 200 days there was no difference in microbial numbers between the pipe materials.

*E. coli* concentrations in biofilms were consistently at or below the detection limit. *E. coli* were detected in biofilms in substantial numbers at the same research site in the aluminum pipes from the same source in the same experimental setup (Pachebsky et al., 2011). Fass et al. (1996) reported that up to 50% of *E. coli* strains injected into a pilot scale water distribution system became attached to the surface of the cast iron pipe, where they proliferated. It remains to be seen which factors control the population of a specific organism in irrigation pipes. We note that literature on drinking water systems presents somewhat contradictory accounts on *E. coli* survival in biofilms. No *E. coli* or coliform bacteria were

cultivated from drinking water biofilms in the work of Schwartz et al. (2003). Juhna et al. (2007) showed that *E. coli* were present in biofilms in drinking water systems in Europe but its detection was strongly dependent on the method used. We would think that such a situation with respect to organism survival is not unique for *E. coli*, and that survival may be site-specific for other organisms in irrigation water distribution systems.

The internal environment of both pipes appeared to be conducive to bacterial survival and growth. Stagnant conditions are known to be preferable for biofilm formation in field conditions (Soini et al., 2002). The internal temperatures in pipes were close to the air temperatures, and stayed within the range suitable for bacterial growth. Differences in weather conditions between sampling days do not provide an explanation for the differences in the biofilm growth rates between sampling dates. Average weekly temperatures monotonously and only slightly increased from 7/17 to 8/7. There was no rainfall before the week of maximum biofilm growth (7/31 to 8/7) whereas a substantial total rainfall of 3 cm occurred before the week of minimum biofilm growth (7/17 to 7/24); factors that could cause qualitative differences in the composition of the creek water as the growth-affecting media. Degradation in microbial water quality within transport pipelines has been shown to be especially pronounced in reclaimed water distribution systems. Jemba et al. (2010) reported regrowth of multiple opportunistic pathogens, including *Legionella* and *Aeromonas*, in treated effluent systems leaving four U.S. municipal wastewater plants. Such regrowth has been associated with the presence of high levels of assimilable organic carbon, which can serve as an energy source for bacterial growth in reclaimed water (Ryu et al., 2005; Weinrich et al., 2010). We note that concentrations of *E. coli* in stream water in this work were at or above the EPA-recommended impairment limit of 235 MPN (100 mL)<sup>-1</sup> which suggests a substantial level of pollution and nutrient availability for bacteria. Surface waters used in irrigation will typically have relatively high nutrient concentrations.

Pipe material was a significant factor affecting the extent of modification microbiological composition of irrigation water. High probabilities of average total coliform and fecal coliform concentrations being the same at intake and in sprinklers were observed more often in aluminum pipes than in plastic pipes; the differences were significant. Differences in input vs. output concentrations were variable in aluminum pipes, whereas output concentrations were consistently marginally higher than intake concentrations in plastic pipes. These data are consistent with biofilm data if it is assumed that bacteria in biofilms were more readily sloughed off from plastic pipes. Bulkier biofilms are more susceptible to shearing action of flowing water (Kim et al., 2010). This may explain the lower biofilm mass consistently found at the location 1 as this location was the first to receive fresh nutrients from the intake water (Fig. 1). Differences in flow conditions have been shown to cause differences in biofilm growth in different parts of irrigation systems (Li et al., 2012).

No nitrates were left in residual water after a week of its storage in the aluminum pipe. Such quick disappearance of nitrates was recently attributed to the action of so called "steady water" that is present between and within porous tubercles, i.e. corrosion-caused prominences on the surfaces of pipes which have a strong ability to reduce nitrates (Nawrocki et al., 2010). Our results seem to conform with this hypothesis. In comparison, new plastic pipes showed only small nitrate concentration decrease (Table 2). If biofilms became anaerobic due to oxygen depletion, it is possible that nitrate was consumed via denitrification, but it is unclear why this would have occurred in aluminum pipes but not on plastic ones.

The increase of phosphorus concentration in plastic pipe is similar to one observed by Lehtola et al. (2004). These authors attributed it to the release organophosphorus additives to the water. We

concur with Lehtola et al. (2004) that data on phosphorus release from specific plastic pipe material to water cannot be generalized to all plastic pipes, given the differences in biofilm formation observed for different plastic types (Yu et al., 2010). We recognize that faucets remained opened and some small evaporative increase of phosphorus concentrations could occur.

Total organic carbon did not show correlations with degree of coliform growth in residual water. This observation is similar to the one of LeChevallier et al. (1991) who noted that although TOC appeared to be associated with coliform regrowth in their work, the TOC levels did not decrease as water moved through the distribution system in their study. They hypothesized that TOC may be a good predictor of growth episodes but may not act as a bacterial nutrient since most of the total organic material is not readily digestible by microorganisms. Average TOC value in residual water was larger than in intake water in all 7 of 8 sampling events (Table 2) which may indicate release of biofilm material to standing water during the week between irrigations.

This work examines biofilms as a potential reservoir for pathogenic bacteria in irrigation distribution systems that can impact the quality of irrigation waters and dissemination of pathogens implicated in food-borne illness. The data show that pipe material has an influence on the development of biofilms in irrigation systems that can serve as a source for microbes. Results of this work are consistent with data from other water distribution systems where microbial community structure and organism numbers have varied as pipe material has changed. It will be important to determine to what extent pathogenic microorganisms can proliferate in biofilms in irrigation systems made of different materials. Finding controls for pathogen accumulation and release in irrigation systems will require resolution of several sampling issues, including the material-specific methods of biofilm extraction, accounting for culturability of organisms extracted from biofilms, and determining the sampling spatial and temporal density of sampling to account for high variability in concentrations and prevalence. Ranges of possible nutrient contents in irrigation waters are very high, so it is important to understand which water, equipment material, and organism properties need to be measured to estimate the risks related to the pathogenic contamination of irrigated plants. Toward this end, it remains to be seen whether feasible disinfection practices, such as flushing, chlorination, etc., have substantially different efficiency with different pipe materials. In any case, because the microbial water quality can be modified while water is transported in an irrigation system, it becomes imperative to monitor the quality of water both coming from sprinklers and at the intake. The quantitative microbial risk assessment of irrigation water (Petterson and Ashbolt, 2003; Mara, 2010) appears to be in need of including the modifications in pipes as an additional factor to evaluate the probabilities of pathogen microorganism exposure. Therefore evaluation of probabilities of concentration modification in pipes as it is done in this work has to be done for pathogens that are shown to be present in irrigation water and potentially important as produce contaminants. Overall, work designed to examine reservoirs of pathogens that can result in crop contamination should include further evaluation of biofilms in irrigation water systems as they may serve as a reservoir for a number of pathogens known to cause food-borne disease.

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